# The Araucaria Project. An improved distance to the Sculptor spiral galaxy NGC 300 from its Cepheid variables


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## ABSTRACT

In a previous paper, we reported on the discovery of more than a hundred new Cepheid variables in the Sculptor Group spiral NGC 300 from wide-field images taken in the B and V photometric bands at ESO/La Silla. In this paper, we present additional VI data, derive improved periods and mean magnitudes for the variables, and construct period-luminosity relations in the V, I and the reddening-independent (V-I) Wesenheit bands using 58 Cepheid variables with periods between 11 and 90 days. We obtain tightly defined relations, and by fitting the slopes determined for the LMC Cepheids by the OGLE II Project we obtain reddening-corrected distances to the galaxy in all bands which show a slight offset to each other in the sense that the Wesenheit relation yields the smallest distance, whereas the I- and V-band distances are by 0.094 mag and 0.155 mag, respectively, larger. We adopt as our best value the distance derived from the reddening-free Wesenheit magnitudes, which is 26.43 $\pm$ 0.04 (random) $\pm$ 0.05 (systematic) mag. The distance moduli from both, the V- and I-bands agree perfectly with the Wesenheit value if one assumes an additional reddening of E(B-V)=0.05 mag intrinsic to NGC 300, in addition to the Galactic foreground reddening towards NGC 300 of 0.025 mag. Such a modest intrinsic reddening is supported by recent HST images of NGC 300 which show that this galaxy is relatively dust-free, but also reveal that there must be *some* dust absorption in NGC 300. We argue that our current distance result for NGC 300 is the most accurate which has so far been obtained using Cepheid variables, and that it is largely free from systematic effects due to metallicity, blending, and sample selection. It agrees very well with the recent distance determination from the tip of the red giant branch method obtained from HST data by Butler et al. (2004), and it is consistent with the Cepheid distance to NGC 300 which was derived by Freedman et al. (2001) from CCD photometry of a smaller sample of stars.

*Subject headings:* distance scale - galaxies: distances and redshifts - galaxies: individual: NGC 300 - galaxies: stellar content - stars: Cepheids

## 1. Introduction

In a previous paper (Pietrzyński et al. 2002; hereafter Paper I), we have reported on the discovery of 117 Cepheids and 12 Cepheid candidates in the Sculptor Group spiral galaxy NGC 300 from B and V images obtained with the Wide Field Imager at the 2.2m telescope at ESO/La Silla, which strongly expanded the number of 18 Cepheids in this galaxy which were known from the earlier pioneering work of Graham (1984), and Freedman et al. (1992). These data have been obtained as part of our ongoing Araucaria Project which seeks to provide improved calibrations of the dependences of several stellar distance indicators, including Cepheids, RR Lyrae stars, red clump giants and blue supergiants, on the environmental properties of their host galaxies (Gieren et al. 2001; see also *http://ifa.hawaii.edu/˜bresolin/Araucaria/index.html*). NGC 300 is one of the principal target galaxies of this project. Our search for additional Cepheid variables in this galaxy was motivated by two goals: first, to derive a more accurate Cepheid-based distance to this nearby galaxy than what was possible from the relatively sparsely sampled light curves of little more than a dozen of Cepheids (Freedman et al. 2001), and this way provide the basis for an accurate calibration of several secondary stellar standard candles; and second, to provide an independent empirical calibration of the effect of metallicity on Cepheid absolute magnitudes, which is very much under dispute at the present time (e.g. Fouqué et al. 2003; Storm et al. 2004). NGC 300 seems well suited for such a calibration, due to the relatively large metallicity gradient in its disk suggested by H II region work (e.g. Deharveng et al. 1988), and whose value has recently been improved by the detailed spectroscopic work of our group on blue supergiant stars in this galaxy which we have been observing with the ESO VLT (Bresolin et al. 2002; Urbaneja et al. 2003, 2004). The relatively strong radial variation of metallicity in the disk of NGC 300, combined with the fact that we have discovered Cepheids over a large range of galactocentric distances, should allow a precise determination of the metallicity effect on their absolute magnitudes. This investigation will be the subject of a forthcoming paper.

While our previous ESO BV imaging data were extremely useful for the purpose of finding a large number of Cepheids in NGC 300, we needed additional I-band data for accurate distance work, to enable us to address the problem of reddening via the reddening-independent (V-I) Wesenheit magnitudes. Some I-band images we had obtained during our previous runs with the ESO Wide Field Imager turned out to suffer from a strong fringing pattern, which we found extremely difficult to correct for in a reliable way. We therefore decided to re-observe NGC 300 in the I (and V) bands using the mosaic cameras attached to the 4-m telescope at CTIO, and to the Warsaw 1.3-m telescope at Las Campanas, which are basically free from this problem. We report on these new data in section 2, and use them together with the data given in Paper I to derive improved periods

for the Cepheids (feasible due to the much enlarged time baseline of the observations), and to construct improved V-band, and I-band light curves for the variables, from which the mean magnitudes are determined. In section 3, we present the period-luminosity relations derived from our data in the various photometric bands which form the basis for the determination of the distance to NGC 300. Our distance determination is presented and discussed in section 4. In section 5, we discuss the sources of uncertainty which affect it, and compare to other determinations of the distance to NGC 300 which have been reported in the literature. Section 6 summarizes our conclusions.

## 2. Observations, Reductions and Calibrations

The new data presented in this paper were collected with the Warsaw 1.3-m telescope at Las Campanas Observatory and the 4-m telescope at CTIO. Each telescope was equipped with a mosaic 8k × 8k detector, with fields of view of about 35 × 35 arcmin and a scale of about 0.25 arcsec/pix. For more instrumental details on these cameras, the reader is referred to the corresponding websites: *http://www.astrouw.edu.pl/~ogle/index.html* *http://www.ctio.noao.edu/mosaic*.

The main body of the new data was obtained with the Warsaw telescope at Las Campanas, but the additional CTIO 4-m observations turned out to be very useful, particularly to improve the I-band light curves of some of the Cepheids in NGC 300. Our new observations started on 2002 October 5 and lasted until 2003 November 11, providing a time baseline of nearly 4.5 years of modern data, together with the previous ESO/WFI observations reported in Paper I, for the determination of improved periods for the Cepheids in NGC 300, and for other variables we have discovered in this galaxy (Mennickent et al. 2004; Bresolin et al. 2004). During the new 2002-2003 period, we secured 30 mosaic images each in the V and I bands, on different nights. The Las Campanas observations were not dithered to compensate for the (small) gaps between the individual CCDs of the mosaic camera; for this reason, we lost a few of the Cepheids presented in the Cepheid catalog of Paper I. Also, some other Cepheids happened to appear too close to the edges of the individual CCDs to be properly calibrated. For these two reasons, we could not obtain I-band light curves for about 20 percent of the total number of Cepheids we had previously discovered in NGC 300. This was, however, not a reason to worry because the total number of Cepheids left to construct the PL relations in the V and I bands in the galaxy is still high enough for very accurate results (see section 4). With few exceptions, the seeing during the new observations was around 1", and sometimes better. Integration times were 900 s per image (in both I and V) with the Warsaw telescope, and 300 s per image with the CTIO

4-m telescope.

Preliminary reductions (i.e. debiasing and flatfielding) of the CTIO data were done with the IRAF[1] "mscred" package. Then, the PSF photometry was obtained for all stars in the same manner as for our WFI data from the ESO/MPI 2.2 m telescope (Paper I). The data from the 1.3 m Warsaw telescope were reduced with the OGLE III pipeline based on the image subtraction technique (Udalski 2003, Woźniak 2000).

To calibrate each of our two data sets onto the standard system we used the extensive sequence of secondary standard stars, distributed over almost the whole observed area, which was established by Pietrzyński, Udalski and Gieren (2002).

## 3. Cepheid Magnitudes and Revised Periods

The new V data obtained at Las Campanas and CTIO were merged with the previous ESO/WFI data reported in Paper I to construct improved V light curves for the Cepheids. Excellent agreement between the different datasets, and in particular between the abundant ESO/WFI and Warsaw 1.3m datasets, was found, with no evidence of zero-point shifts between the datasets for individual Cepheids amounting to more than 0.03 mag. Generally, it was not possible to detect *any* evidence for a zero point offset between the different datasets, which could in principle occur if the zero point was varying over the respective fields of the cameras we used. From our data, we can limit the size of such an effect, if existent at all, to less than 0.03 mag in both filters. The result of merging the V data are light curves of exquisite quality for most of the variables, especially for the brighter, longer-period Cepheids which carry the largest weight in the distance determination (see section 4). In this process, we were able to improve the periods for a substantial fraction of the Cepheids, by fitting together our own datasets now spanning more than 4 years, and by combining them with the older CCD data of Freedman et al. (1992) for those Cepheids which had already been known and observed prior to our wide-field study. While for most of the Cepheids the periods derived in Paper I were basically confirmed, and only slight modifications were found necessary, for a few of the stars, marked in Table 1 (our revised Cepheid catalog), we found evidence for periods changing in time. Among these stars with evidence for a variable period are the variables cep002 (V12), and cep005 (V3). Both stars have periods in excess of $50^d$ and therefore masses in the 10-13 $M_\odot$ range, and we could be witnessing a continuous change in their pulsation periods caused by their relatively fast

[1]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

evolutionary migration across the Cepheid instability strip which takes about $10^5$ yrs for the second crossing, and only $\sim 10^3$ yrs for the third crossing (Bono et al. 2000). Future monitoring of these stars will allow us to determine the period changes more precisely to check on this interesting possibility.

The I-band light curves were constructed from our new data, adopting the periods derived from the analysis of the V-band data. They are of excellent quality for most of the longer-period stars, but even for the shorter-period, fainter Cepheids in our sample they are of good quality for most of the stars. Only for the shortest-period Cepheids in our sample, less than about 10 days, the I-band light curves become quite noisy, as expected at the combination of telescope size and integration times we were using in the acquisition of these data. In some cases, we combined the new I-band magnitudes with those of Freedman et al. for common stars (whenever this procedure led to an improved light curve from the combined datasets-this was not always the case) before calculating the mean magnitudes. We also note here that there was no evidence for any significant zero point offset between the Freedman et al. data and our own data, in neither of the two bands. We had demonstrated this already for the V-band light curves in Paper I. This adds to our confidence that our adopted photometric zero-points in both, V and I are accurate to $\sim$0.03 mag.

Table 1 presents the catalog of Cepheid data for all the variables having both V- and I-band light curves from our observations, and pulsation periods longer than 10 days (64 stars). We do not include in Table 1 the Cepheids with periods less than 10 days because they were not used in the distance determination for reasons discussed in section 5. Finding charts for each of these variables were given in Paper I, as were their coordinates. We do not repeat the mean magnitudes in the B band for these objects-they were reported in Paper I, and have not changed because we did not re-observe the stars in the B filter. The entries in Table 1 are the revised periods, the revised epochs of maximum brightness (in HJD) in V, and the intensity mean magnitudes in V (derived by Fourier series fitting to our own datasets), I (from our own new datasets reported in this paper, merged with the Freedman et al. (1992) data whenever this increased the light curve quality), and the reddening-free (V-I) Wesenheit magnitude $W_I$ (defined as $W_I$ = I - 1.55 (V-I); see Udalski et al. 1999). The formal uncertainties on the intensity mean magnitudes in all bands, as returned from the Fourier fitting routine, are always in the range 0.01-0.02 mag. Their small sizes reflect the high quality of the light curves for most of the variables. The periods in Table 1 replace the values given in Paper I, as do the mean V magnitudes. To demonstrate the quality of our data, we show the V- and I-band light curves for some of the Cepheids of our sample in Fig. 1. These light curves are representative for the average quality of the light curves of other Cepheids in our sample of similar period. Fig. 2 shows a Cepheid light curve in V

and I in which we have distinguished the different datasets with different symbols, in order to demonstrate the very good agreement among them. Such a good agreement is seen for nearly all the Cepheids, albeit the noise in some light curves is larger.

Table 2 contains the individual new V and I observations for all the Cepheids in Table 1. The full Table 2 is available in electronic form.

## 4. The Distance Modulus of NGC 300

From the data given in Table 1, we constructed the period-luminosity relations for the Cepheids in NGC 300 in V, I and $W_I$. We excluded the one star in our Table having a period longer than 100 days, cep001. The reason is that at periods exceeding 100 days, previous evidence seems to indicate that the Cepheid PL relation might change its slope and become nearly flat (see, for instance, Fig. 4 in Freedman et al. 1992). Such an effect is also predicted from theoretical models (Bono et al. 2002). Indeed, cep001 with its period of 115 days is more than half a magnitude fainter than what we would expect from the PL relations defined by all the other stars. Besides this (probably) peculiar Cepheid, we rejected 5 Cepheids due to their large deviations from the mean PL relations in one, or several bands. These variables are marked in Table 1. They all have relatively short periods (where we have many Cepheids, and their relative weight in the fits is therefore low). We note, however, that their inclusion in the fits and distance solutions would introduce only very minor, insignificant changes in the PL relations in the different bands, and in the resulting distance to NGC 300. We chose a short-period cutoff period of 10 days for the construction of the PL relations for several reasons. First, inspection of the PL relations in V and B which were constructed from our previous, smaller dataset in Paper I (Fig. 10 there) shows that a Malmquist bias (Sandage 1988) is present for periods shorter than about 10 days. This is due to the photometric detection limit in our data - we start to miss the intrinsically faint Cepheids at periods less than about 10 days (the ones lying below the ridge line in the Cepheid instability strip). For periods of 10 days or longer, we are obviously not limited by this Malmquist bias anymore, and our stars can be expected to fill the Cepheid instability strip in a homogeneous way. A second reason to omit the very short-period stars in our Cepheid sample is the fact that these, intrinsically relatively faint Cepheids are more susceptible to blending than the longer-period, brighter Cepheids. We discuss the effect of blending on our distance results in more detail in section 5, but remark here that using only the longer-period Cepheids for distance determinations will protect us, to a larger extent, against the possible effect of unresolved companion stars on the solutions. The third reason to exclude Cepheids of period less than 10 days in our solutions

is the fact that just downwards from about this period, the light curves (particularly those in I which were basically measured at a 1.3m telescope) become too noisy, increasing the random uncertainty in our distance solution.

In Figs. 3 and 4, we show the period-luminosity (PL) relations in the V and I bands obtained from the 58 Cepheids adopted for the final distance solutions. These figures show that our data define a tight PL relation in the V band, and an even tighter relation in the I band, which is expected due to the smaller intrinsic width of the Cepheid instability strip toward longer wavelengths, and to the reduced influence of a possible differential extinction inside the galaxy. It is seen that there is no evidence for curvature in the relations at the shortest periods, indicating that our choice for the value of the cutoff period is adequate. We de-reddened our V and I mean magnitudes adopting a Galactic foreground reddening to NGC 300 of E(B-V)=0.025 mag (Burstein & Heiles 1984), and an extinction law of $A_V$=3.24 E(B-V), and $A_I$=1.96 E(B-V) (Schlegel et al. 1998). There might of course exist some additional absorption produced inside NGC 300; however, there are reasons to believe that such an intrinsic absorption is small (see discussion in Freedman et al. 1992), which seems to be confirmed by the recent high-resolution image obtained for NGC 300 with HST and which has been published in the Hubble Heritage Project, showing that NGC 300 is indeed relatively free of dust. In any case, our adopted approach for eliminating any influence of reddening on our results, or at least reduce it to the lowest possible level, is to use the reddening-free Wesenheit PL relation for the distance solution. We display the $W_I$-log P relation from our data in Fig. 5. Again, the data define a relationship which is evidently linear over the whole period range from 10-90 days we use, and whose dispersion is, as expected, somewhat smaller than the one of the I-band PL relation.

In order to derive the NGC 300 distance from the Wesenheit PL relation, we decided to adopt the slope for this relation as established by Udalski (2000) from the LMC Cepheids. There are two reasons for this choice. First, the slopes and zero points of the Cepheid PL relations in the LMC in W, as well as in V and I, are extremely well established from the OGLE II Project (Udalski et al. 1999; Udalski 2000). Second, there is some evidence that the slope of the Cepheid PL relation might depend, to some degree, on metallicity (e.g. Storm et al. 2004; Tammann et al. 2003; for a more detailed discussion on this point, see section 5). To minimize any possible systematic effect of metallicity on our distance determination for NGC 300, especially in view of the current uncertainty of the effect a changing metallicity has on Cepheid absolute magnitudes, it seems wise to use the PL slopes derived in a galaxy which has a similar mean metallicity as the target galaxy under study. From our recent spectroscopic work on blue supergiant stars in NGC 300 (Urbaneja et al. 2003, 2004) we now know that the mean metallicity of these stars, which are quite evenly distributed over the disk of NGC 300, is about -0.3 to -0.4 dex, which is practically identical

to the mean LMC metallicity for the young stellar population, including Cepheids (Luck et al. 1998). Therefore it is, in the case of NGC 300, certainly the best choice to adopt the PL relation slopes determined by the OGLE II Project in the LMC. Nevertheless, we also did "free fits" to the data, without pre-specifying the slopes. These yield values of -3.01 $\pm$ 0.16, -3.12 $\pm$ 0.12, and -3.29 $\pm$ 0.11 for the PL relation slopes in V, I and $W_I$, respectively. These values compare very well with the corresponding OGLE II LMC slopes of -2.775, -2.977 and -3.300, supporting our choice. Particularly in the Wesenheit band, the agreement of the NGC 300 PL relation slope with that defined by the LMC Cepheids is striking-the values are virtually identical. The agreement of the slopes determined from the NGC 300 Cepheids with the ones obtained from Galactic Cepheids whose distances have been measured with the near-infrared surface brightness technique of Fouqué & Gieren (1997) (see Gieren, Fouqué & Gómez 1998; Storm et al. 2004) is not as good, the Galactic Cepheid slopes being steeper than the slopes we observe in NGC 300, particularly in the Wesenheit band which is the most important one for the distance determination. We suspect that this difference is caused by the higher average metallicity of the Galactic Cepheid sample.

Using the OGLE II slopes given above, we derive the following equations for the PL relations in NGC 300:

$$V_0 = \text{-}2.775 \log P + (25.155 \pm 0.034) \qquad \text{rms}=0.275 \text{ mag}$$

$$I_0 = \text{-}2.977 \log P + (24.621 \pm 0.025) \qquad \text{rms}=0.205 \text{ mag}$$

$$W_I = \text{-}3.300 \log P + (23.802 \pm 0.028) \qquad \text{rms}=0.198 \text{ mag}$$

The rms dispersions around these mean relations are somewhat larger, but quite comparable, to those for the Galactic Cepheid PL relations (Storm et al. 2004), which seems quite remarkable for such a faint and distant sample of stars, and reinforces the very good quality of our data.

Combining the OGLE II LMC PL relation zero points (Udalski, 2000) in the three photometric bands with those of the previous equations, we obtain the distance of NGC 300, *with respect to the LMC*, directly by taking the difference (ZP(NGC 300) - ZP(OGLE II). This can be transformed to an *absolute* distance to NGC 300 by adding the adopted LMC distance modulus. Without going into the difficult discussion about the true value of the LMC distance modulus here (see Benedict et al. 2002; Walker 2003; Feast 2003), we adopt as the current best distance modulus to the LMC the value 18.50. With this adopted

distance to the LMC, we find the following distance moduli for NGC 300, in the 3 different bands we study:

$(m - M)_0$ ($W_I$) = 26.434 mag

$(m - M)_0$ (I) = 26.528 mag

$(m - M)_0$ (V) = 26.589 mag

Whereas the values from the 3 different bands agree quite closely among each other, there *is* some scatter beyond the random uncertainties on these numbers (see section 5). We adopt the distance coming from the reddening-free Wesenheit index as our best result. This is also supported by the fact that the Wesenheit relation shows the smallest scatter of the three relations, and its observed slope is in truly perfect agreement with the slope defined by the LMC Cepheids.

Why do the I- and V-band data yield slighly larger distance moduli? A straightforward and very reasonable explanation is that our adopted Galactic foreground absorption is insufficient, and that we have neglected some contribution to E(B-V) intrinsic to NGC 300. Indeed, assuming an average *intrinsic* (to NGC 300) reddening of E(B-V)=0.05 mag, in addition to the foreground E(B-V)=0.025 mag, the distance moduli derived from *both*, I and V, converge, within 0.01-0.02 mag, to our adopted NGC 300 distance modulus from the Wesenheit PL relation, and we have a completely consistent solution from the three bands.

A possible concern in our way to compare the samples of Cepheids in the LMC and NGC 300 is the fact that the mean periods of the two samples are quite different, the mean period of the LMC sample observed by the OGLE II Project being much shorter. It is therefore interesting to repeat the above analysis, for comparison, on the subsample of OGLE II LMC Cepheids having periods larger than 10 days, just as our adopted NGC 300 sample. Recently, Kanbur et al. (2003) has identified some long-period Cepheids in the OGLE sample which have problems like strange shapes of their light curves, large phase gaps in their light curves, or unusually low light curve amplitudes. Taking out such stars from the sample, we get a "clean" sample of 45 LMC Cepheids with periods in excess of 10 days. If we fit the same slopes as given above (obtained by Udalski (2000) from the full sample of Cepheids of all periods) to the PL relations defined by these 45 long-period LMC Cepheids, and compare the resulting zero points (very slightly different from the zero points coming from the full sample of LMC Cepheids) to the NGC 300 zero points in the different bands, we get almost *exactly* the same distance to NGC 300 from the Wesenheit magnitudes (26.444 mag, instead of 26.434 mag). The offsets of the distances now obtained in the V and I bands to the W band are slightly smaller than above, and are consistent with an additional internal reddening in NGC 300 of 0.03 mag, as compared to the 0.05

mag we derived above. It is therefore evident that our derived distance to NGC 300 does not depend on introducing a period cutoff of 10 days in the LMC sample, in order to make its mean period comparable to our NGC 300 sample, or just working with the complete sample of LMC Cepheids of all periods.

## 5. Discussion

In this section, we are discussing the sources of error which may affect our distance result, and will try to estimate their effect as realistically as possible. We will not discuss the current uncertainty of the LMC distance modulus (which clearly remains the largest source of systematic error in the adopted absolute distance to NGC 300)-regarding this problem, the reader is referred to the papers of Walker (2003), Feast (2003), and Benedict et al. (2002), and references given therein.

### 5.1. Photometry

An obvious source of systematic uncertainty on our distance result is in the adopted zero points of our photometry. We already mentioned that our different datasets are very consistent among themselves, excluding systematic zero point variations among the datasets exceeding  0.03 mag, both in V and I. This is of course not surprising because we used identical standard stars and reduction procedures for all our datasets. The comparison with the Freedman et al. (1992) photometry for the Cepheids in common supports the conclusion that zero point errors are not exceeding 0.03 mag. We already discussed the possibility that in addition to a systematic zero point error in our photometry, there could be a slight zero point variation over the mosaic detectors we used. A comparison of our different datasets for all the Cepheids in our database (which appear in very different positions on the detectors) convinced us that such an effect, if at all present, must be very small, certainly less than 0.03 mag. In any case, such an effect would not be systematic, but just add to the random scatter in our derived mean magnitudes of the Cepheids.

### 5.2. Sample Selection for the Construction of the PL Relations

In the previous section, we have already discussed the reason for adopting a period cutoff of 10 days for our sample. The introduction of this cutoff effectively eliminates any significant contribution to the systematic error on our NGC 300 distance result from a

Malmquist bias due to the Cepheid detection limit set by our photometry. It assures that the filling of the Cepheid instability strip in the period range adopted for our study is homogeneous, and near-complete, given the large number of Cepheids (58) we were able to use in our study. It also eliminates any possibility that our sample is contaminated by the inclusion of overtone Cepheids. These stars do only appear at periods smaller than about 8 days, as has been impressingly demonstrated by the different microlensing projects (OGLE, MACHO, EROS) in the LMC.

In order to investigate if there is any dependence of our distance result on the adopted value of the cutoff period, we also did solutions using period cutoffs of log P=1.2, 1.4 and 1.5. In all cases, the distance results were the same within 0.03 mag, but the uncertainty in the zero point of the solutions increases as a result of having less stars for the fits. We can therefore be sure that our result is very robust regarding the choice of the cutoff period, as long as this is large enough to eliminate the problems due to Malmquist bias.

### 5.3. Adopted Slopes of the Period-Luminosity Relations

In the previous section, we already discussed the reason for adopting the slopes derived for the LMC Cepheids by the OGLE II team. We believe that these reasons are very strong. A reason of concern in using them for our current study might be the fact that the OGLE II slopes are mostly based on Cepheids having periods smaller than 10 days while we use only Cepheids with periods larger than 10 days in NGC 300, but we have shown in the previous section that this has no significant effect on our distance solution.

Several of the authors of this paper have made a great effort in the past to calibrate the *Galactic* Cepheid PL relation with a high accuracy (Gieren et al. 1998; Storm et al. 2004). Yet, the current precision we have achieved from the measurement of the distances of some 40 Galactic Cepheids cannot compete with the results for the LMC coming from several hundreds of stars. The Galactic PL relation, if future work confirms that it is significantly different from the LMC relation, will be useful in the study of galaxies which have near-solar metallicity. In the case of NGC 300, it seems definitively preferable, from all the points of view we mentioned, to use the OGLE LMC PL relations to derive an accurate, albeit relative, distance for this galaxy, which can be scaled to any LMC distance which might be adopted in the future, in the light of new results.

### 5.4. Metallicity Effects

The question of how chemical abundances affect the absolute magnitudes of Cepheid variables, and how such a possible metallicity dependence translates into a shift in the zero points of the PL relations in different photometric bands, has been the subject of a longstanding debate. Yet, a clear answer to this question is still missing. All the observational tests which have been carried out over the years (for a recent review, see Fouqué et al. 2003; see also the recent paper of Sakai et al. 2004) have suffered from the low accuracy of the reported results; therefore, the metallicity effect remains largely unconstrained, at the present time. At least, evidence seems to be hard enough now to determine the sign of the effect: more metal-poor Cepheids are, at any given period, intrinsically fainter than their more metal-rich counterparts, at least at visible wavelengths, but by which amount is very uncertain. Clearly, more stringent tests will have to be made, and it has been one of the principal motivations for our group to discover Cepheid variables in NGC 300 to carry out such an improved test. For the time being, it is clearly the best strategy to minimize metallicity-related effects in Cepheid-based distance determinations by comparing samples of Cepheids having the same average metallicity. Given that the mean metallicity of NGC 300 is very close to that of the LMC (references cited before), we are quite confident that there is no significant contribution to our error budget from any metallicity-related effect. The expected variation in metallicity among the Cepheids in our sample (a few tenths of 1 dex) could introduce some additional dispersion in our PL relations, but such an effect is obviously quite small (see section 5.6.).

### 5.5. Reddening

In our approach, we have circumvented the problem of applying appropriate reddening corrections by using the reddening-independent Wesenheit magnitudes. The relatively low scatter in the $W_I$-log P relation in Fig. 4 demonstrates that the random errors in the mean magnitudes of the Cepheids in V and I are low enough to successfully apply this method. The fact that we do not see a *dramatic* reduction in the scatter of this relation, as compared to the I-band PL relation, is likely to be a consequence of the fact that the reddening, including possible differential reddening inside NGC 300, is evidently small in the case of NGC 300, which already helps to reduce the scatter in the reddening-dependent V- and I-band PL relations. The fact that a small additional reddening of 0.05 makes our distance results from V, I and W fully consistent lends additional support to our conclusion that our distance result is not significantly biased due to an unproper treatment of reddening.

Just to stress the relative independence of our distance result for NGC 300 on

reddening, we mention that if we adopt a constant reddening of E(B-V)=0.10 mag for the Cepheids in the LMC as done by Fouqué et al. 2003 (instead of the variable reddening from the OGLE maps), and use the resulting very slightly changed OGLE II PL relations for the LMC, we obtain a Wesenheit distance of 26.40 mag for NGC 300, instead of our adopted value of 26.43 mag. The difference is clearly not significant and reinforces our conclusion that the effect of reddening on our result is very small.

### 5.6. Crowding Effects

At the distance of NGC 300, crowding is clearly an issue at the typical resolution of 1 arcsec of our images. Probably to each of the variables there are a few very nearby stars which are not resolved in the images and therefore contribute to the measured fluxes of the Cepheids. The effect is systematic because it makes the Cepheids too *bright*, and therefore, if the effect is significant, makes the derived distance too small. While it is quite difficult to quantify the effect blending may have on the distance we derive for NGC 300, there are several indications that the effect is very small. One reason comes from the observed relatively small rms scatter in all bands, which can be explained just by the random scatter in the mean magnitudes due to the quality of our photometry, the intrinsic width of the instability strip, some contribution from differential reddening in the V- and I-band PL relations, and possibly a small metallicity-related term due to the fact that the Cepheids in our sample will have a dispersion in their individual metallicities of a few tenths of a dex. If a significant fraction of the Cepheids would be heavily blended such that their observed fluxes are significantly altered, they should stand out towards the bright end in the PL relations, and this should increase the rms dispersion in the relations. There is very little evidence for this to occur in our data. Also, we have protected ourselves against such an effect by eliminating those Cepheids which show a very large deviation from the mean relations, and three of the five eliminated objects are indeed very bright (see Figs. 3-5) and could be stars blended with exceptionally bright nearby companions. A second reason why we think that our distance is not significantly affected by the blending problem is that we do not see any indication of a flattening of the PL slopes towards the short-period end in the PL relations. It can be reasonably assumed that blending will, on average, affect the short-period Cepheids more strongly than the longer-period ones because they are intrinsically fainter, by up to 3 magnitudes. If blending is a serious issue, we should then expect a higher fraction of overluminous Cepheids close to our short period cutoff than at larger periods. This should flatten the slope towards short periods (just as the Malmquist bias, but for a totally different reason). We tested for this by adopting successively larger cutoff periods up to log P=1.4; in all cases, the slopes of the resulting PL relations do

not show any evidence for a significant increase. For the arguments given, we believe that our distance determination is not significantly affected by the problem of unresolved nearby stars. Fortunately, Cepheids are intrinsically very bright stars and therefore their susceptibility to blending is small.

Summarizing the previous discussion, our conclusion is that we have a total random error of 0.04 mag from the photometric noise, and a possible slight zero point variation over the CCD, and a total systematic uncertainty which amounts to 0.05 mag, and whose main contributor is the uncertainty of our adopted overall photometric zero points in I and V. We therefore find a final result for the distance to NGC 300 of

$$(m - M)_0 = 26.43 \pm 0.04 \text{ (random)} \pm 0.05 \text{ (systematic) mag}$$

This distance result compares very favorably with the previous determination of Freedman et al. (2001) who obtained a true distance modulus of 26.53, adopting the same value (18.50) for the LMC distance modulus, and the same PL relation slopes from the OGLE II Project. It is consistent with this value within the combined 1 $\sigma$ uncertainties. It is also clearly consistent, within the combined uncertainties, with another recent HST-based determination of the distance to NGC 300 from the I-band magnitude of the tip of the red giant branch, which yielded a distance modulus of 26.56 ± 0.07 (± 0.13)mag (Butler et al. 2004).

## 6. Conclusions

We have used a large number of wide-field images in the V and I bands which have been obtained over almost four years at ESO, Las Campanas and CTIO to discover a large number of Cepheid variables in the Sculptor spiral galaxy NGC 300. Our images have been carefully analyzed and calibrated, and we have used the long-period Cepheids in the galaxy ($P \geq 10 days$) to establish the period-luminosity relations in the V, I and $W_I$ bands. The definition of these relations from our data is excellent, and their slopes agree very well with those found by Udalski et al. (1999) for the Cepheids in the LMC. In order to minimize metallicity-related effects on our distance determination, we used the LMC slopes to fit our NGC 300 sample, given that the mean metallicity for both galaxies appears to be the same. The fit to the reddening-independent Wesenheit PL relation yields our best, adopted distance to NGC 300 of 26.43 mag, with small statistical (0.04 mag) and systematic (0.05 mag) uncertainties. This value assumes that the LMC distance is 18.50 mag, but can be scaled to any different value of the LMC distance if this turns out to be appropriate in the light of future work. We find somewhat longer distances from the V- and I-band PL

relations assuming a Galactic foreground reddening of E(B-V)=0.025; if we postulate an additional reddening of 0.05, intrinsic to NGC 300, the distances obtained from the V and I bands agree perfectly with that derived from the reddening-independent W band. The distance derived in this paper is the most accurate one so far measured to NGC 300 from Cepheid variables, but it agrees well with the previous determination of Freedman et al. which was based on CCD photometry of a much smaller sample of variables. Our distance determination is also consistent with the recent determination of Butler et al. from the TRGB method, using I-band images obtained with the Hubble Space Telescope. The distance to NGC 300 seems therefore to be well established now. To confirm this, and hopefully further improve the accuracy of our current result, we will use near-infrared Cepheid PL relations in a study which will be carried out soon. NGC 300 will then be a key galaxy to calibrate secondary stellar methods of distance determination, as we are proposing to do in our Araucaria Project.

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Table 1. Cepheids in NGC 300

| ID | P [days] | log P | $T_0 - 2450000$ | $< V >$ | $< I >$ | $< W_I >$ | Remarks |
|---|---|---|---|---|---|---|---|
| cep001 | 115.8 | 2.0637 | 2952.5 | 20.134 | 19.162 | 17.655 | rejected from the fit |
| cep002 | 89.06 | 1.9497 | 2911.65 | 19.712 | 18.696 | 17.121 | period variable ? |
| cep003 | 83.00 | 1.9191 | 1543.57 | 19.258 | 18.490 | 17.300 | |
| cep004 | 75 | 1.8751 | 2607 | 19.776 | 19.029 | 17.871 | |
| cep005 | 56.599 | 1.7528 | 1391.862 | 20.412 | 19.599 | 18.339 | period variable ? |
| cep006 | 52.751 | 1.7222 | 2965.566 | 20.465 | 19.549 | 18.129 | |
| cep007 | 43.35 | 1.6370 | 1547.60 | 20.917 | 19.917 | 18.367 | |
| cep008 | 40.29 | 1.6052 | 2853.85 | 20.317 | 19.586 | 18.453 | |
| cep009 | 36.74 | 1.5651 | 2871.77 | 21.068 | 20.220 | 18.906 | |
| cep010 | 35.58 | 1.5512 | 2907.66 | 21.264 | 20.210 | 18.576 | |
| cep012 | 34.999 | 1.5439 | 2899.708 | 20.869 | 20.015 | 18.691 | |
| cep013 | 34.75 | 1.5410 | 1408.85 | 20.828 | 19.893 | 18.444 | |
| cep014 | 33.975 | 1.5312 | 2928.635 | 20.701 | 19.886 | 18.623 | |
| cep015 | 32.29 | 1.5091 | 2859.79 | 21.006 | 20.155 | 18.836 | |
| cep016 | 28.41 | 1.4535 | 2853.85 | 21.339 | 20.275 | 18.626 | |
| cep018 | 25.003 | 1.3980 | 1488.572 | 21.446 | 20.666 | 19.457 | |
| cep019 | 24.79 | 1.3943 | 2911.65 | 21.583 | 20.703 | 19.339 | |
| cep022 | 24.24 | 1.3845 | 2849.81 | 21.609 | 20.828 | 19.617 | |
| cep023 | 24.037 | 1.3809 | 2849.819 | 21.893 | 20.903 | 19.369 | |
| cep026 | 23.444 | 1.3700 | 2903.740 | 21.227 | 20.426 | 19.184 | |
| cep027 | 23.35 | 1.3683 | 2911.65 | 21.271 | 20.369 | 18.971 | |
| cep028 | 23.12 | 1.3640 | 2916.65 | 20.992 | 20.341 | 19.332 | |
| cep029 | 22.79 | 1.3577 | 1519.58 | 21.808 | 20.786 | 19.202 | |
| cep030 | 22.21 | 1.3465 | 2907.66 | 21.533 | 20.618 | 19.200 | |
| cep032 | 21.07 | 1.3237 | 2856.85 | 21.424 | 20.700 | 19.578 | |
| cep035 | 19.485 | 1.2897 | 2916.658 | 21.460 | 20.733 | 19.606 | |
| cep036 | 18.91 | 1.2767 | 1519.59 | 22.469 | 21.406 | 19.758 | |
| cep038 | 18.24 | 1.2610 | 2552.53 | 21.543 | 20.873 | 19.834 | |
| cep039 | 18.31 | 1.2627 | 1438.84 | 22.165 | 21.216 | 19.745 | |
| cep040 | 18.219 | 1.2605 | 1484.641 | 21.478 | 20.745 | 19.609 | |
| cep041 | 18.012 | 1.2556 | 2952.562 | 21.441 | 20.751 | 19.681 | |
| cep043 | 17.833 | 1.2512 | 2552.540 | 21.515 | 20.804 | 19.702 | |
| cep044 | 17.22 | 1.2360 | 2898.70 | 22.055 | 21.275 | 20.066 | |

Table 1. Cepheids in NGC 300 - continued

| ID | P [days] | log P | $T_0 - 2450000$ | $< V >$ | $< I >$ | $< W_I >$ | Remarks |
|---|---|---|---|---|---|---|---|
| cep045 | 16.92 | 1.2284 | 1438.84 | 21.664 | 20.838 | 19.558 | |
| cep046 | 16.56 | 1.2191 | 2860.80 | 22.499 | 21.551 | 20.082 | |
| cep048 | 16.49 | 1.2172 | 2851.79 | 21.623 | 20.987 | 20.001 | rejected from the fit |
| cep049 | 16.10 | 1.2068 | 2849.81 | 22.085 | 20.951 | 19.193 | |
| cep050 | 15.92 | 1.2019 | 2928.63 | 21.762 | 21.005 | 19.832 | |
| cep051 | 15.70 | 1.1959 | 2886.69 | 22.053 | 21.248 | 20.000 | |
| cep052 | 15.61 | 1.1934 | 2879.76 | 21.575 | 20.813 | 19.632 | |
| cep053 | 15.49 | 1.1901 | 2907.66 | 22.225 | 21.375 | 20.057 | |
| cep055 | 15.0 | 1.1761 | 2911.6 | 22.190 | 20.994 | 19.140 | rejected from the fit |
| cep056 | 15.05 | 1.1775 | 1516.62 | 21.666 | 21.183 | 20.434 | rejected from the fit |
| cep058 | 14.80 | 1.1703 | 2907.66 | 22.039 | 21.123 | 19.703 | |
| cep059 | 14.56 | 1.1632 | 1488.57 | 22.117 | 21.455 | 20.429 | rejected from the fit |
| cep060 | 14.411 | 1.1587 | 1491.590 | 22.149 | 21.347 | 20.104 | |
| cep061 | 14.24 | 1.1535 | 2851.79 | 22.299 | 21.421 | 20.060 | |
| cep062 | 14.355 | 1.1570 | 1431.835 | 22.075 | 21.097 | 19.581 | |
| cep063 | 14.361 | 1.1572 | 2879.768 | 21.952 | 21.102 | 19.784 | |
| cep065 | 14.045 | 1.1475 | 2879.768 | 21.848 | 21.091 | 19.918 | |
| cep066 | 13.856 | 1.1416 | 2911.659 | 22.046 | 21.205 | 19.901 | |
| cep067 | 13.754 | 1.1384 | 2903.740 | 22.338 | 21.524 | 20.262 | |
| cep069 | 13.605 | 1.1337 | 1547.610 | 22.325 | 21.367 | 19.882 | |
| cep070 | 13.523 | 1.1311 | 2849.819 | 22.027 | 21.292 | 20.153 | |
| cep071 | 13.443 | 1.1285 | 2641.660 | 21.893 | 21.217 | 20.169 | |
| cep072 | 13.505 | 1.1305 | 2946.688 | 22.340 | 21.280 | 19.637 | |
| cep073 | 13.464 | 1.1292 | 1431.837 | 21.881 | 21.067 | 19.805 | |
| cep074 | 13.358 | 1.1257 | 1433.828 | 21.930 | 21.198 | 20.063 | |
| cep076 | 13.168 | 1.1195 | 1488.572 | 21.857 | 20.901 | 19.419 | rejected from the fit |
| cep077 | 12.94 | 1.1119 | 2916.65 | 22.230 | 21.430 | 20.190 | |
| cep079 | 11.951 | 1.0774 | 2911.659 | 22.053 | 21.298 | 20.128 | |
| cep081 | 11.579 | 1.0637 | 2911.659 | 22.287 | 21.582 | 20.489 | |
| cep082 | 11.497 | 1.0606 | 2903.740 | 22.635 | 21.765 | 20.416 | |
| cep085 | 11.2 | 1.0492 | 1524.6 | 22.208 | 21.457 | 20.293 | |

Table 2. Individual New V and I Observations

| object | filter | HJD-2450000 | mag | $\sigma_{mag}$ |
|---|---|---|---|---|
| cep001 | V | 2641.660400 | 19.734 | 0.013 |
| cep001 | V | 2849.819092 | 20.670 | 0.024 |
| cep001 | V | 2851.790527 | 20.634 | 0.025 |
| cep001 | V | 2856.855957 | 20.527 | 0.026 |
| cep001 | V | 2857.820557 | 20.507 | 0.021 |
| cep001 | V | 2859.794189 | 20.489 | 0.031 |
| cep001 | V | 2860.801270 | 20.444 | 0.032 |
| cep001 | V | 2861.866699 | 20.360 | 0.036 |
| cep001 | V | 2863.755127 | 20.303 | 0.058 |
| cep001 | V | 2871.775635 | 19.868 | 0.014 |
| cep001 | V | 2879.768311 | 19.633 | 0.011 |
| cep001 | V | 2886.691406 | 19.801 | 0.019 |
| cep001 | V | 2893.736572 | 19.907 | 0.039 |
| cep001 | V | 2898.709229 | 19.916 | 0.019 |
| cep001 | V | 2899.708008 | 19.911 | 0.014 |
| cep001 | V | 2903.740479 | 19.989 | 0.012 |
| cep001 | V | 2907.663086 | 20.001 | 0.015 |
| cep001 | V | 2911.659668 | 20.010 | 0.013 |
| cep001 | V | 2916.658203 | 20.076 | 0.021 |
| cep001 | V | 2922.662354 | 20.186 | 0.053 |
| cep001 | V | 2928.635498 | 20.223 | 0.017 |
| cep001 | V | 2932.641846 | 20.288 | 0.015 |
| cep001 | V | 2939.582520 | 20.501 | 0.024 |
| cep001 | V | 2946.688965 | 20.655 | 0.043 |
| cep001 | V | 2952.562744 | 20.776 | 0.028 |

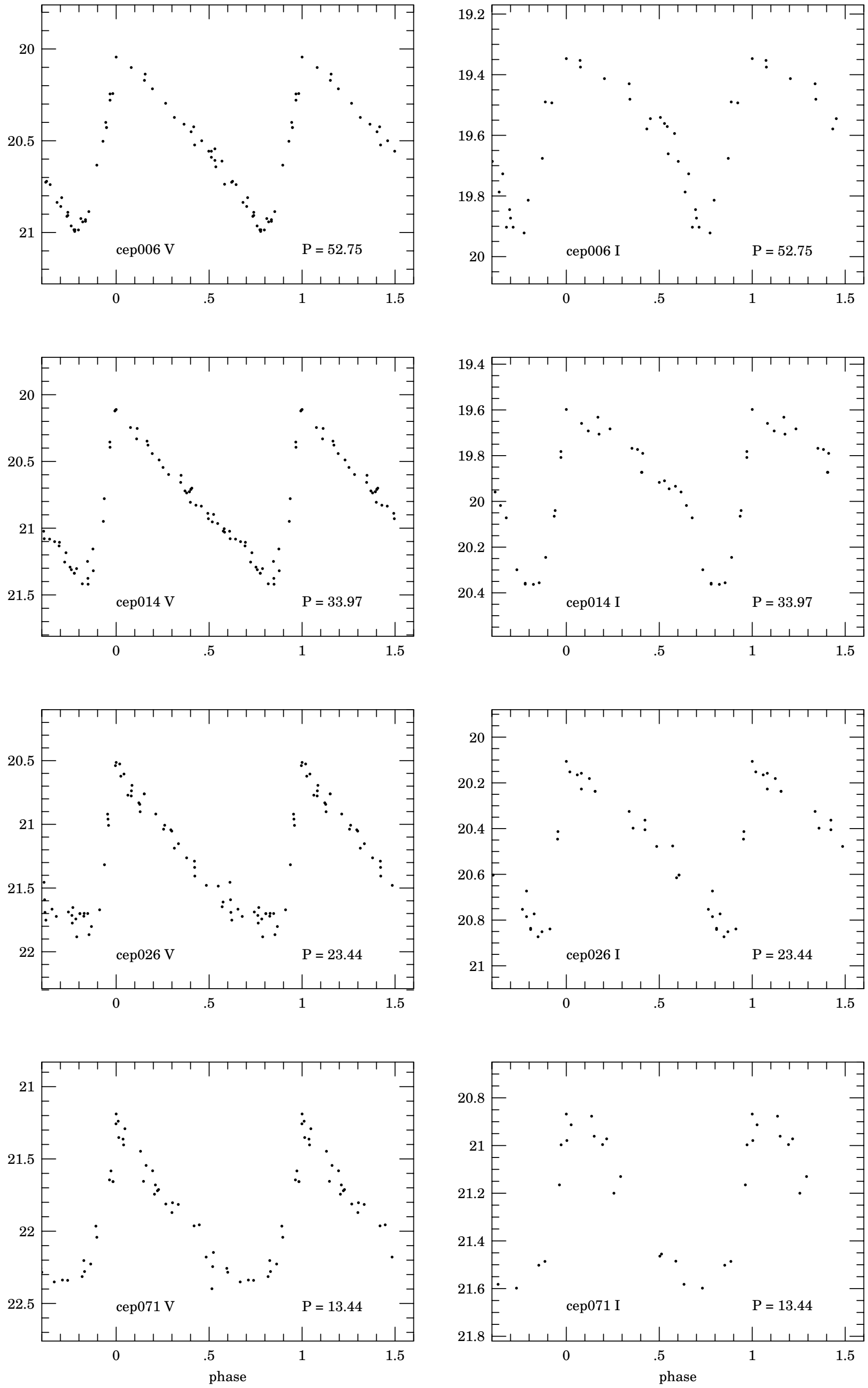


Fig. 1.— Phased V- and I-band light curves for Cepheids of different periods in our NGC 300 sample.

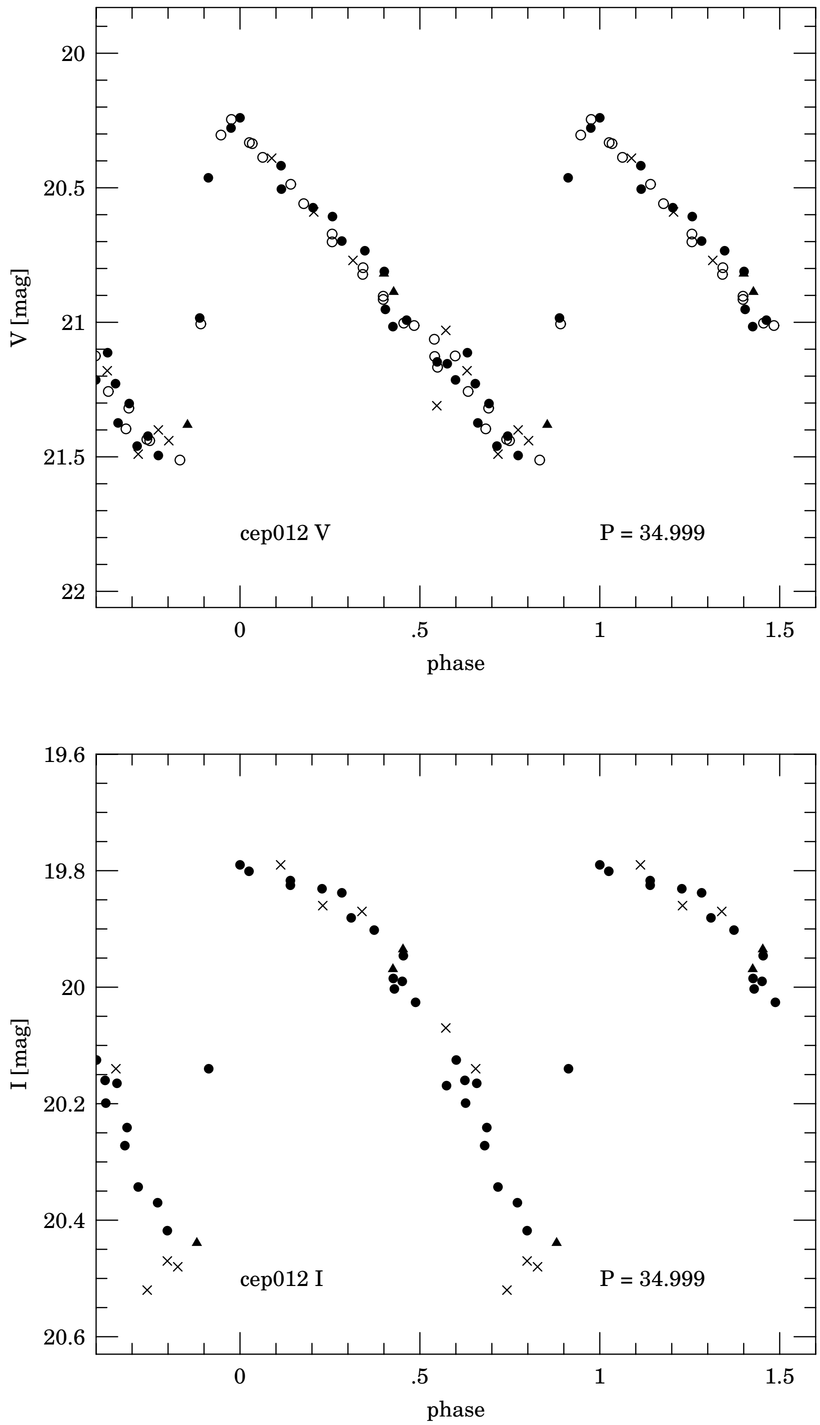


Fig. 2.— The phased V- and I-band light curves of the NGC 300 Cepheid cep012. Filled circles, our new Warsaw 1.3 m data. Open cicles, our previous ESO/WFI data. Filled triangles, our new CTIO 4 m observations. Crosses, data from Freedman et al. (1992). The good agreement of the different datasets is evident.

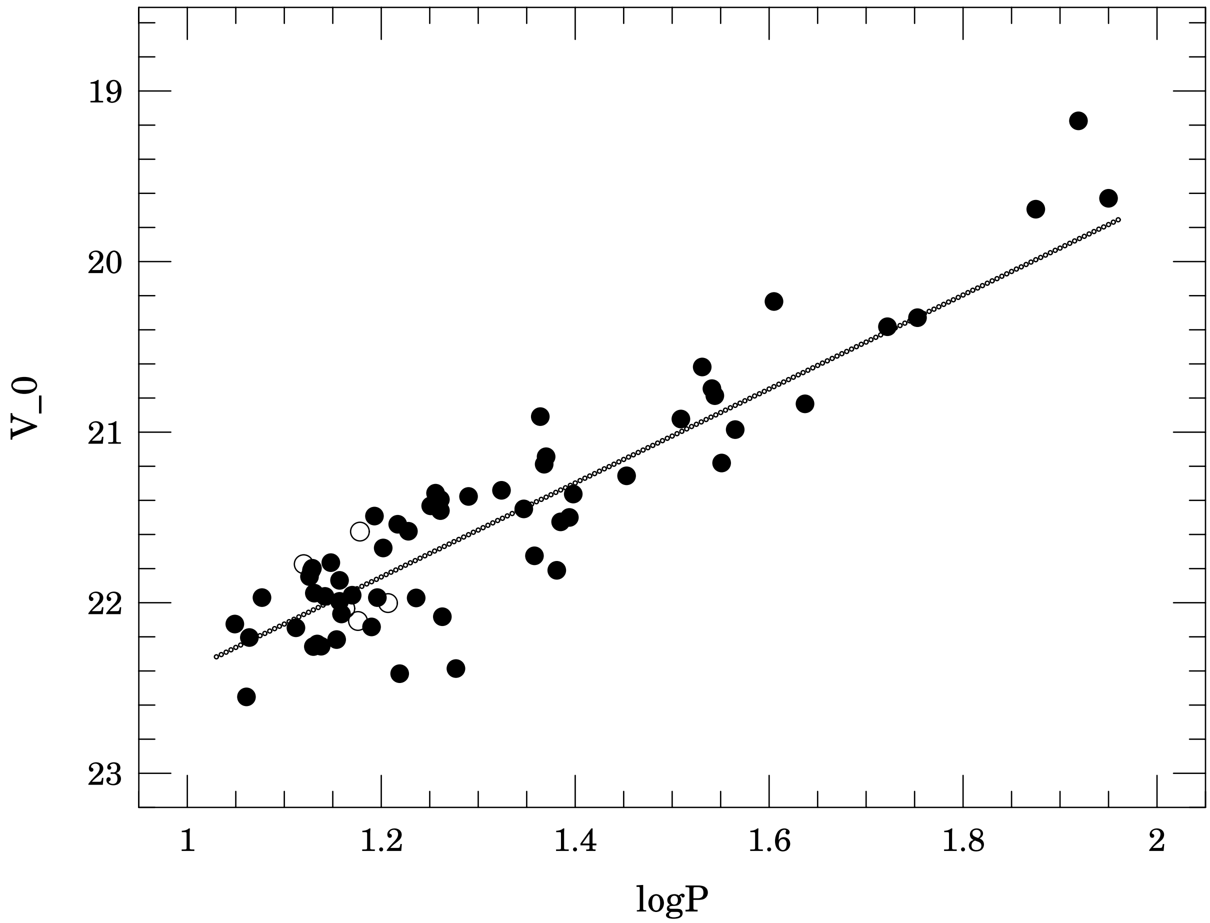


Fig. 3.— The period-luminosity relation for NGC 300 Cepheids in the V band. Open circles denote variables not used in the distance determination. The slope of the relation was adopted from the LMC Cepheids (OGLE II).

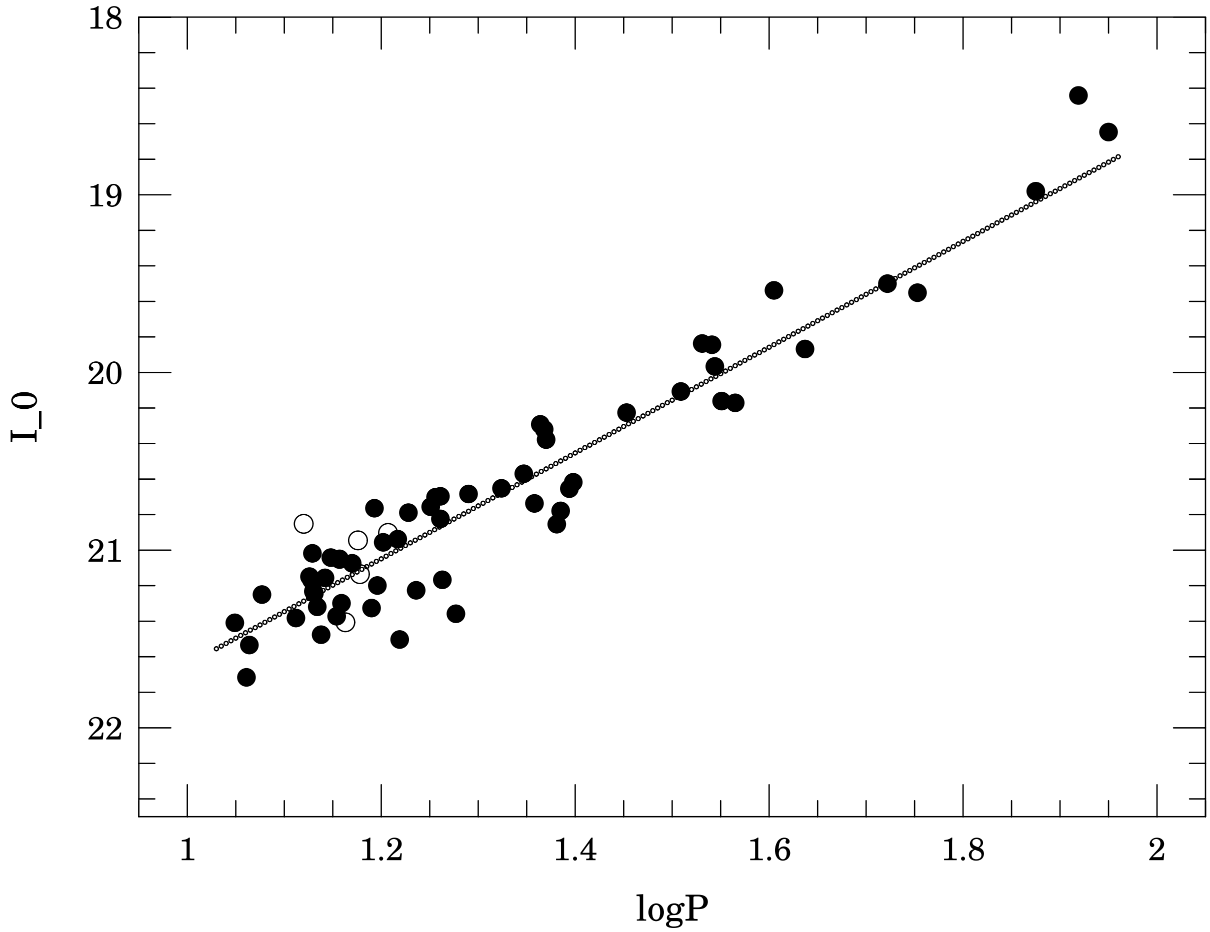


Fig. 4.— Same as Fig. 3, for the I band.

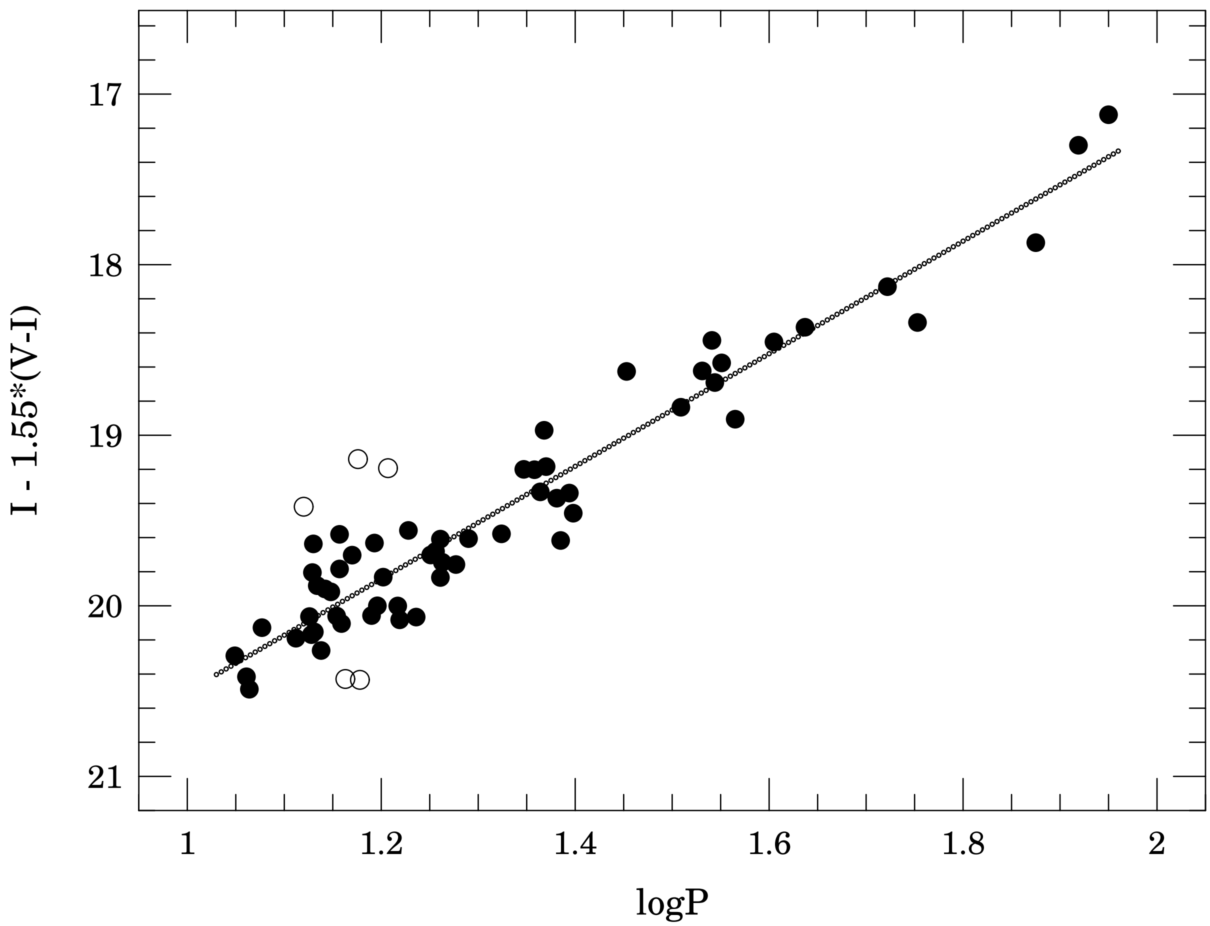


Fig. 5.— Same as Fig. 3, for the reddening-independent (V-I) Wesenheit magnitudes.